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Thermo-Economic Optimization of Solar Assisted Heating and Cooling (SAHC) System

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ABSTRACT: The energy demand for cooling is continuously increasing due to growing thermal loads, changing architectural modes of building, and especially due to occupants indoor comfort requirements resulting higher electricity demand notably during peak load hours. This increasing electricity demand is resulting higher primary energy consumption and emission of green house gases (GHG) due to electricity generation from fossil fuels. An exciting alternative to reduce the peak electricity consumption is the possible utilization of solar heat to run thermally driven cooling machines instead of vapor compression machines utilizing high amount of electricity. In order to widen the use of solar collectors, they should also be used to contribute for sanitary hot water production and space heating. Pakistan lying on solar belt has a huge potential to utilize solar thermal heat for heating and cooling requirement because cooling is dominant throughout the year and the enormous amount of radiation availability provides an opportunity to use it for solar thermal driven cooling systems. The sensitivity analysis of solar assisted heating and cooling system has been carried out under climatic conditions of Faisalabad (Pakistan) and its economic feasibility has been calculated using maximization of NPV. Both storage size and collector area has been optimized using different economic boundary conditions. Results show that optimum area of collector lies between 0.26m² to 0.36m² of collector area per m² of conditioned area for i_{eff} values of 4.5% to 0.5%. The optimum area of collector increases by decreasing effective interest rate resulting higher solar fraction. The NPV was found to be negative for all i_{eff} values which shows that some incentives/subsidies are needed to be provided to make the system cost beneficial. Results also show that solar fraction space heating varies between 87 and 100% during heating season and solar fraction cooling between 55 and 100% during cooling season which indicates a huge amount of conventional energy saving potential.

Keywords: Solar cooling and heating, solar collector, absorption chiller, NPV, PBT

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1. Introduction

Solar thermal collector systems used only for sanitary/domestic hot water (SHW/DHW) production usually do not exploit at their full capacity due to high amount of solar heat available in the summer and lower SHW demand, and as a result show a rather low specific collector yield, even if with a rather high solar fraction (Arboit *et al.* 2012).

The basic idea of solar assisted heating and cooling (SAHC) system lies in the exploitation of most efficient solar thermal collectors producing hot water all round the year. During winter, the solar thermal heat/energy can be utilized to provide space heating to the buildings and sanitary hot water for kitchen purposes while during summer months, the solar thermal energy/heat can be effectively utilized by providing it to thermal operated sorption chiller to produce chilled water.

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Therefore, the annual exploitation factor of solar thermal collectors can be enhanced even for the cases for which the demand of SHW is low. Apparently, the interesting eccentricity of SAHC systems is the cooling operation because its demand schedule for cooling coincides with possible ease of use of sun radiation. In contrast, conventional/traditional vapour compression systems (electricity driven) provide minimum cooling capacity during hot sunny hours of a day. In comparison with conventional vapor compression chillers (VCC)/air-conditioners, solar thermal cooling systems can save upto 80% of electricity for same cooling capacity especially for office buildings due to its matching schedule of cooling demand and radiation availability (Guo & Shen 2009; Thomas & Andre 2009; Jaunzems & Veidenbergs 2010).

Nomenclature

Ac	Area of collector	COP	Coefficient of performance
Cel	Electricity cost	CNG	Natural gas rate
E	Energy	FPC	Flat plate collector
I	Initial investment	i	Annual interest rate
ieff	Effective interest rate	j	Energy price increase rate
SAHC	Solar Assisted Heating and Cooling	NPV	Net Present Value
n	Life in years	Pc	Peak power demand cooling
Ph	Peak power demand heating	PBT	Payback time
Qdem,C	Space cooling energy demand	Qdem,H	Space heating energy demand
Qdem,SHW	Energy demand SHW	R	Cost of fuel savings using solar energy
SF	Solar fraction	SHW	Sanitary hot water
V	Storage volume	Φ	Local latitude

A little research work has been carried out in the last few years in the field of SAHC systems for optimal design and cost beneficial solutions. Eicker & Pietruschka (2008) investigated solar system to fulfil heating and cooling demand of office buildings under diverse climatic conditions of Europe. The cost analysis revealed that locations in Southern European having higher cooling load results significantly lower costs. Particularly, for extended operation hours, the unit cost of cooling produced are nearly 200 € MWh^{-1}, and increases to 280 € MWh^{-1} for small cooling loads and internal gains (Eicker & Pietruschka 2008). Florides *et al.* 2001 described simulation model prepared using TRNSYS software for a building in Cypriot location. This model is a result of various built-in components/units e.g. different type of solar thermal collectors, auxiliary/backup heating sources, pumps, storage tanks, thermal operated chiller, thermostats and building demand/loads. The simulations were performed by varying important design parameters e.g. thermal storage tank volume, solar thermal collector area, etc. and analysis was carried out in terms of its energy production, economics and environmental aspects. A parametric optimization was also carried out focusing at enhancing the system performance to generate energy. This optimization was not devoted to measure the set of system operating parameters to reduce cost of the system (Florides *et al.* 2001; Florides *et al.* 2001). Assilzadeh *et al.* 2005 also performed similar study for a building in Malaysian using the simple scheme of SHC system. Simulation software allowed establishing the optimum area of solar thermal collector and tilt angle. A simulations/sensitivity analysis were also carried out by changing collector tilt angle and area, storage tank volume, pump flow rate and auxiliary boiler set-point temperatures. This analysis did not aim at determination of the optimum values of operating parameters (Assilzadeh *et al.* 2005). Similar, studies were also carried out by Gaddhar *et al.* 1996 to perform optimization based on economics for solar plant used for cooling in Beirut (Gaddhar *et al.* 1996).

In solar thermal systems, solar collector cost is dominant and generally lies between 50 and 80 % of the overall system cost. However, increasing conventional energy sources (fossil fuel) prices, decreasing capital investment costs and technical improvements (design and efficiency) in solar collectors may favor solar thermal cooling installations in near future (Syed *et al.* 2002).

This paper focus to optimize the area of collector and storage tank for SAHC system based on maximization of Net Present Value (NPV) using a conventional/traditional system as reference for an office building under climatic conditions of Faisalabad (Pakistan). A widely spread simulation software namely PolySun® has been used to perform sensitivity analysis of solar assisted heating and cooling system.

2. Types of heating and cooling systems

Building space heating and air-conditioning can be fulfilled using different methods. A conventional method

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consisting of a boiler is used for SHW/DHW production and space heating during winter season while VCC is used for cooling/air-conditioning purposes. The conventional vapor compression chillers/air-conditioners use high amount of electricity resulting heavy load on the national grid. However, space heating and cooling can also be done using solar energy in the form of electricity to operate heat pump or solar thermal energy to operate sorption chiller. A thermal driven chiller is used to produce cooling while same collector is utilized for space heating in winter using a backup boiler in case of scarce or no radiation. In this paper attention has been paid to solar thermal driven heating and cooling system.

2.1 General description of reference/conventional heating and cooling system

The conventional/traditional space heating and cooling system consists mainly of two units: Boiler (for space heating and SHW) and vapor compression chiller (for cooling/air-conditioning). A natural gas boiler is employed to provide the required space heating to the office building during winter period while SHW is required from November to March. In this system cooling effect (cooling/air-conditioning) is produced by using a conventional vapor compression chiller driven by electric energy from the national grid during the cooling period. Vapor compression cooling systems require chlorofluorocarbons (CFC) and hydro-chlorofluorocarbons (HCFC) as working fluids which cause global warming effect (GWE) and ozone (O_3) depletion of different extent (Duffie & Beckman 2006; Aguilar & Cai 2010; Arent, Wise & Gelman 2011; Popp, Hascic & Medhi 2011).

2.2 General description of Solar assisted heating and cooling system

In SAHC system, the vapor compression chiller is replaced with thermal driven sorption chiller, while heat is supplied to sorption chiller using solar thermal collectors and back-up auxiliary heating unit. The major components of SAHC system includes solar thermal collectors (FPC or ETC), hot water storage tank (buffer storage), back-up auxiliary unit (the same gas boiler used for heating in winter season in reference case), sorption chiller (absorption or adsorption), heat rejection system (dry cooler/wet cooling tower), fan coils for heating and cooling distribution and pumps and controllers.

The heat supply required by an absorption chiller can be calculated using cooling demand of the building and COP of absorption chiller using Eq. (1).

$$Q_{ab,H} = \frac{Q_{dem,C}}{COP_{ab}} \quad \textbf{(1)}$$

Where:

- $Q_{ab,H}$ is heat required by an absorption chiller (kWh)
- $Q_{dem,C}$ is the cooling energy demand of the building (kWh)
- COP_{ab} is COP of an absorption chiller (-)

A cooling tower (dry or wet type) is required to reject heat at intermediate temperature to the ambient and is the summation of heat supplied to the absorption unit at higher temperature and heat extracted from the building at low temperature as shown in Eq. (2).

$$Q_{rej,CT} = Q_{ab,H} + Q_{ab,C} \quad \textbf{(2)}$$

Where:

- $Q_{rej,CT}$ is the heat rejected to ambient by cooling tower

3. Methodology

3.1 Peak powers and energy demand of the office building

An office building has been selected for this analysis because the operation schedule of an office building matches well with the solar energy availability minimizing the use of backup boiler during nighttime. The building space heating and cooling demand depends upon geographical site,conduction/convection/radiation losses, infiltration and ventilation losses, internal heat gains (people, equipment, and artificial light), passive solar gains, and indoor set-point temperatures. The city of Faisalabad lies on a latitude of 31.42^{o} N with average ambient temperature of 23.8 ^{o}C. The analysis has been carried out for the medium size office building having conditioned area of 600m^2. The main characteristics of the selected building are shown in Table 1.

The peak power for space heating and cooling, annual/seasonal heating and cooling energy demand and energy demand for SHW production for the selected office building are given in Table 2. The monthly heating and cooling demand of the building is shown in Figure 1. The figure clearly indicates the cooling dominant situation of the selected location.

3.2 Sensitivity analysis and optimization methodology of SAHC system

The economics analysis for solar assisted heating and cooling system is performed and the collector size is optimized on the basis of NPV without taking into account any incentives/subsidies. The built-in scheme

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for SAHC system is selected and modified from the PolySun catalogue to perform sensitivity analysis (Figure 2).

The most common thermal/heat driven technology to produce chilled water is absorption cooling due to its simpler capacity control, higher reliability, easier implementation, silent operation, longer life and low maintenance cost. Therefore, a commercially available H_2O-LiBr absorption chillers (rated power 60kW) was selected depending upon their peak cooling demand to meet the cooling load of the selected building. Flat plate collector (FPC) was selected for SAHC system due to its local availability and lower market price.

Table 1
Characteristics of medium size office building

Parameter	Value	Unit
Occupants density	0.06	Person/m^2
Total surface area of the building	978	m^2
Total volume of the building	1620	m^3
Average U-value of the building	1.02	W $m^{-2}K^{-1}$
Internal heat gains by people	4.8	W/m^2
Internal heat gains by equipment	10	W/m^2
Internal heat gains by light (peak)	9	W/m^2
Set-point temperature for space heating	20 ± 0.5	^oC
Set-point temperature for space cooling	26 ± 0.5	^oC
Sanitary hot water (SHW) set point temperature	45	^oC

Table 2
Peak powers and total seasonal heating and cooling demand of the building

Building Parameter	Symbol	Value	Unit
Peak power demand space heating	P_h	27	kW
Space heating energy demand	$Q_{dem,H}$	8040	kWh
Peak power demand space cooling	P_c	56	kW
Cooling energy demand	$Q_{dem,C}$	47486	kWh
Energy demand for SHW	$Q_{dem,SHW}$	1157	kWh

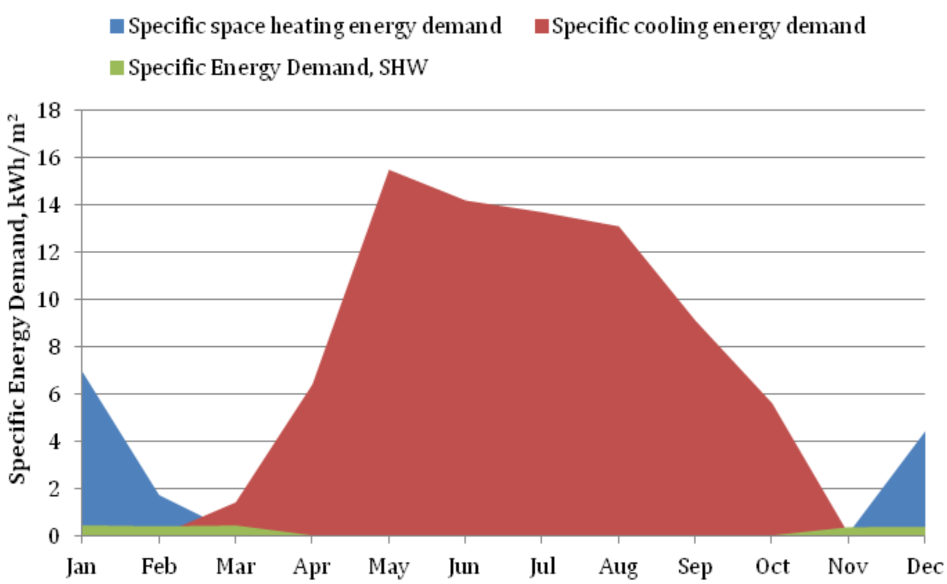

Fig. 1 Specific energy demand for SHW, space heating and cooling of the building

To optimize solar systems, different economical methods have been employed [6]. Among these methods, Net Present Value (NPV) method, also called as Life Cycle Savings (LCS) method, is a rather simple and comprehensive method used for economics evaluation, which includes the initial system investment and annual operating and maintenance cost discounted to present value (PV) as shown in Eq. (3).

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$$NPV = -I + R\frac{(1+i_{eff})^n - 1}{i_{eff}(1+i_{eff})^n} - M\frac{(1+i)^n - 1}{i(1+i)^n} \quad (3)$$

Where:

- I is initial investment (€)
- R is cost of fuel savings using solar energy (€)
- n is life in years and ieff is effective interest rate

The effective interest rate is calculated using Eq. (4).

$$i_{eff} = \frac{(i_{ann} - j)}{(1+j)} \quad (4)$$

Where:

- i_{ann} is annual interest rate
- j is energy price increase rate

The effect of other parameters e.g. insurance, tax and maintenance has not been taken into account. In this analysis different combinations of effective interest rates (i_{eff}) as a function of annual interest rate (i_{ann}) and energy price increase rate (j) has been considered for comparison purposes ranging from 0.5% to 4.5% with a step of 1%. The electricity and natural gas rate is taken as 0.1105 and 0.060 € kWh^{-1} respectively.

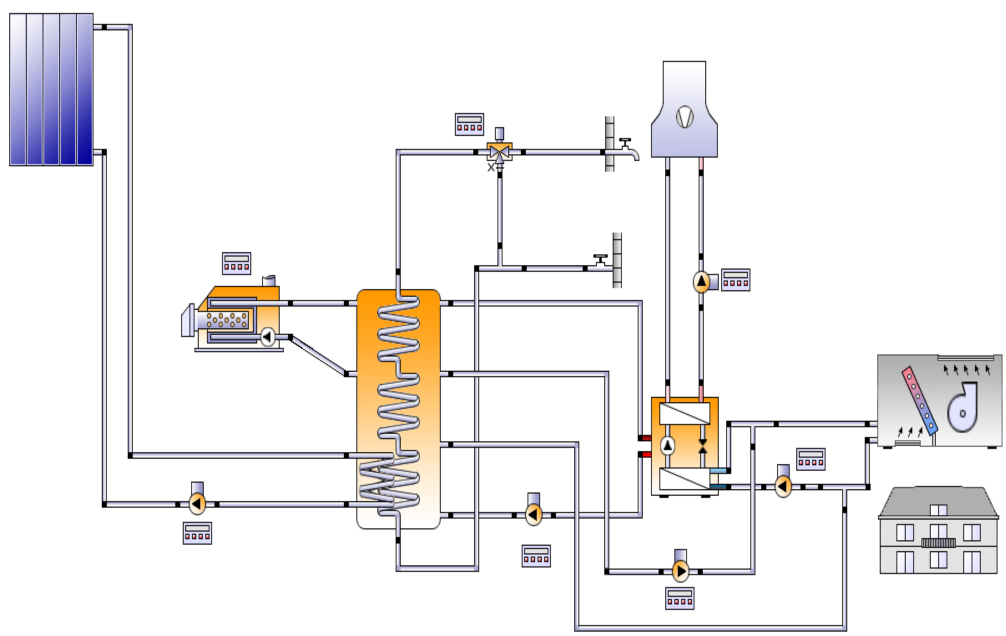

Fig. 2 Scheme of SAHC system (Velasolaris 2010)

4. Results and Discussion

4.1 Sensitivity analysis and economic evaluation of conventional system

The initial investment and operating/running costs for conventional/reference system has been calculated. The operating cost is calculated using total primary fuel energy required for space heating and SHW production and electricity required running vapor compression chiller. The total primary (fuel) energy consumption and electricity (for pumps) required for space heating and SHW production was calculated by performing sensitivity analysis using PolySun reference scheme for space heating and SHW production, while electricity required to run vapor compression chiller/air-conditioner is calculated as the ratio of cooling energy demand to average COP of the vapor compression chiller. The overall annual energy consumed in reference/conventional system is shown in Table 3.

4.2 Sensitivity analysis and optimization of SAHC system

The tilt angle was optimized for the city of Faisalabad keeping other system parameters fixed, while changing the tilt angle which results optimum value of tilt angle for the collector as Φ (local latitude) minus 11°.

The storage tank size was also optimized by few authors stating that the storage capacity between 50 and 110 lt m^{-2} gives best results for solar thermal systems, but above 70 lt m^{-2} no significant variation of solar fraction (SF) was noticed (Mateus & Oliveira 2009). It is

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worth mentioning here that these results have been provided based on energy analysis but optimization has not been performed considering economic aspect. Therefore, storage tank has also been optimized for each area of collectors maximizing NPV for selected location considering local climatic and economic parameters. Results are shown in Figure 3. From this analysis the best fit curve for optimum storage equation is given by $V=85Ac^{0.96}$.

Table 3
Energy consumption of reference/conventional system

Quantity	Symbol	Unit	Value
Energy consumption (Fuel used) for space heating and SHW	E_{aux}	kWh	12933
Average COP	COP	-	2.8
Total electricity consumption (Epumps+Eel,VCC)	$E_{el,tot}$	kWh	16965

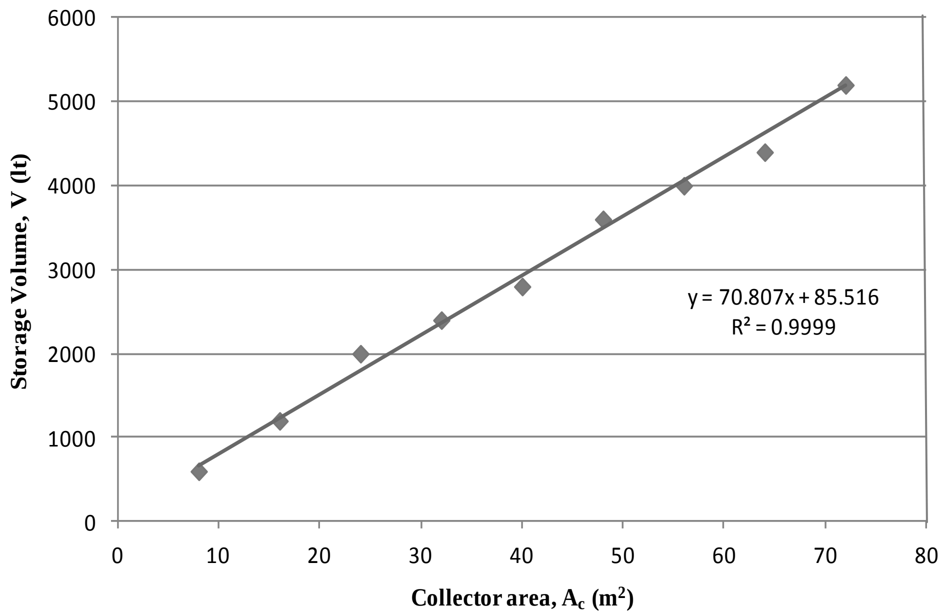

Fig. 3 Best fit curve for optimum storage equation

To compare the optimum storage size, different storage size coefficient and the corresponding equations have been adopted as shown below;
K=70; V=70Ac as storage tank size ST1
$K=70/Ac^{0.1}$; $V=70Ac^{0.9}$ as storage tank size ST2
$K=60/Ac^{0.2}$; $V=60Ac^{0.8}$ as storage tank size ST3
$K=70/Ac^{0.3}$; $V=70Ac^{0.7}$ as storage tank size ST4
$K=70/Ac^{0.5}$; $V=70Ac^{0.5}$ as storage tank size ST5
$K=60/ Ac^{0.5}$; $V=60 Ac^{0.5}$ as storage tank size ST6

The comparison of specific storage volume for optimum storage equation with other storage equations is shown in Figure 4. The figure shows that optimum specific storage volume is not constant for increasing area of collectors. It is higher for smaller area of collectors and decreases with larger area of collectors and vice versa.

The comparison of NPV, SF and specific collector yield for optimum storage volume and other storage equations with respect to different area of collector is shown in Figures 5, 6 & 7 respectively. The NPV for optimum storage volume is slightly higher compared to other storage tank sizes giving maximum value at 216m^2 of collector area. It is important to mention here that SF and specific collector yield of optimum storage equation is slightly higher before 128m^2 for all storage sizes while at 128m^2 the specific optimum storage volume is equal to ST1 and above 128m^2 of collector area the specific optimum storage sizes decreases that results slight decrease in SF and specific collector yield compared to ST1.

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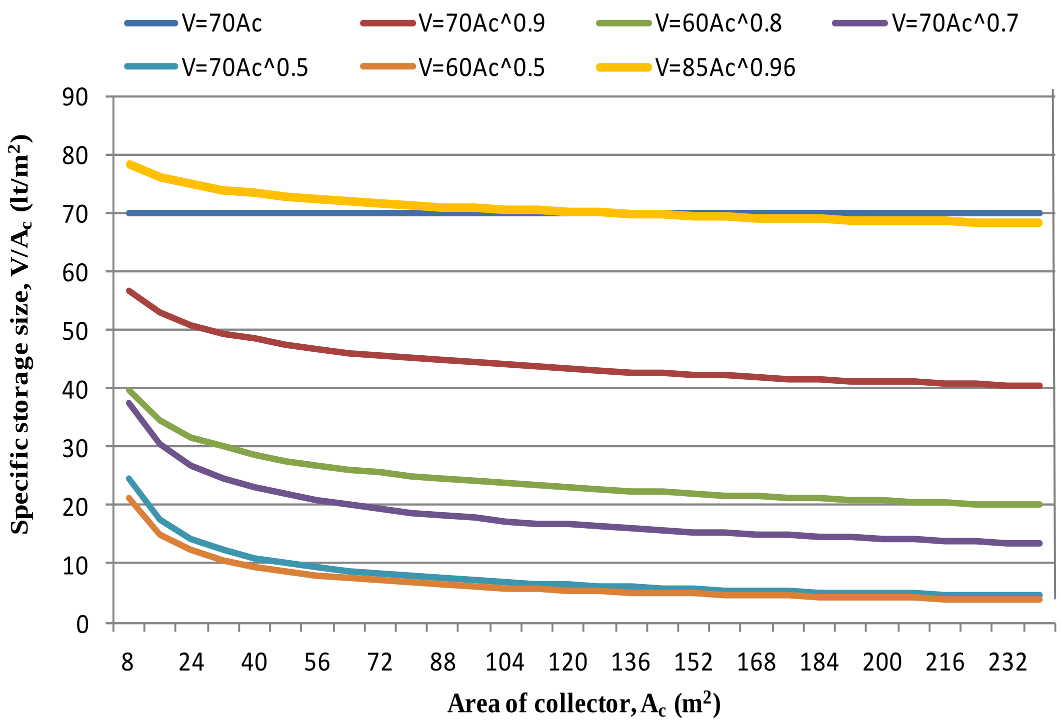

Fig. 4 Optimum storage equation comparison with different storage sizes

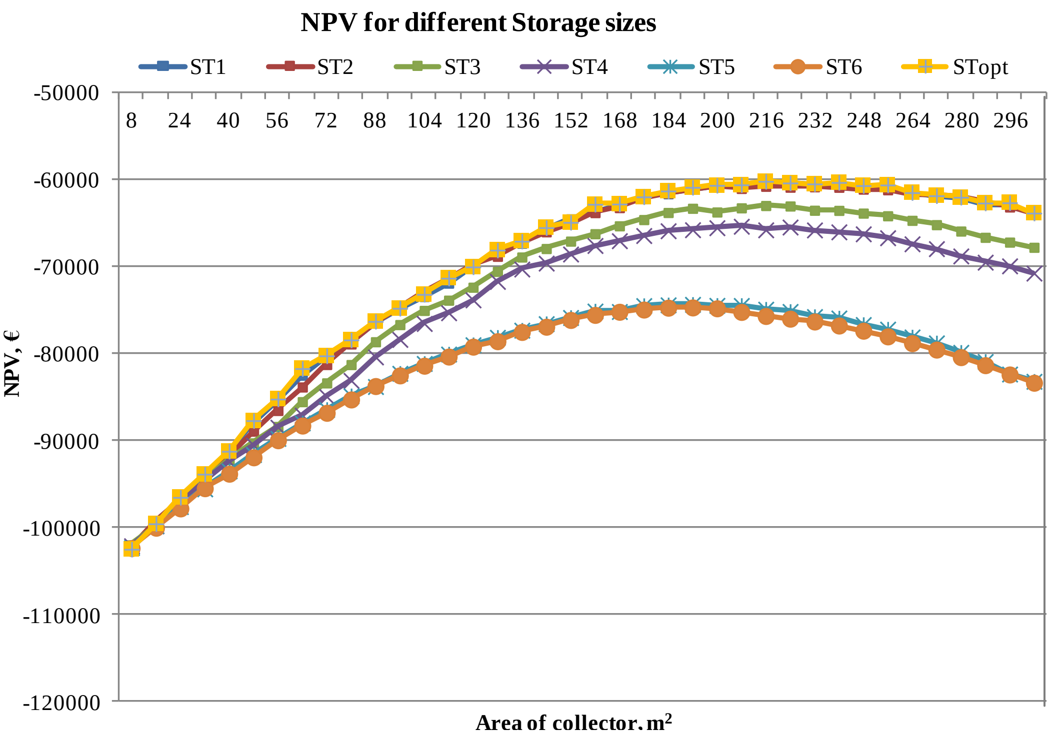

Fig. 5 Comparison of NPV for optimum storage size with different storage sizes

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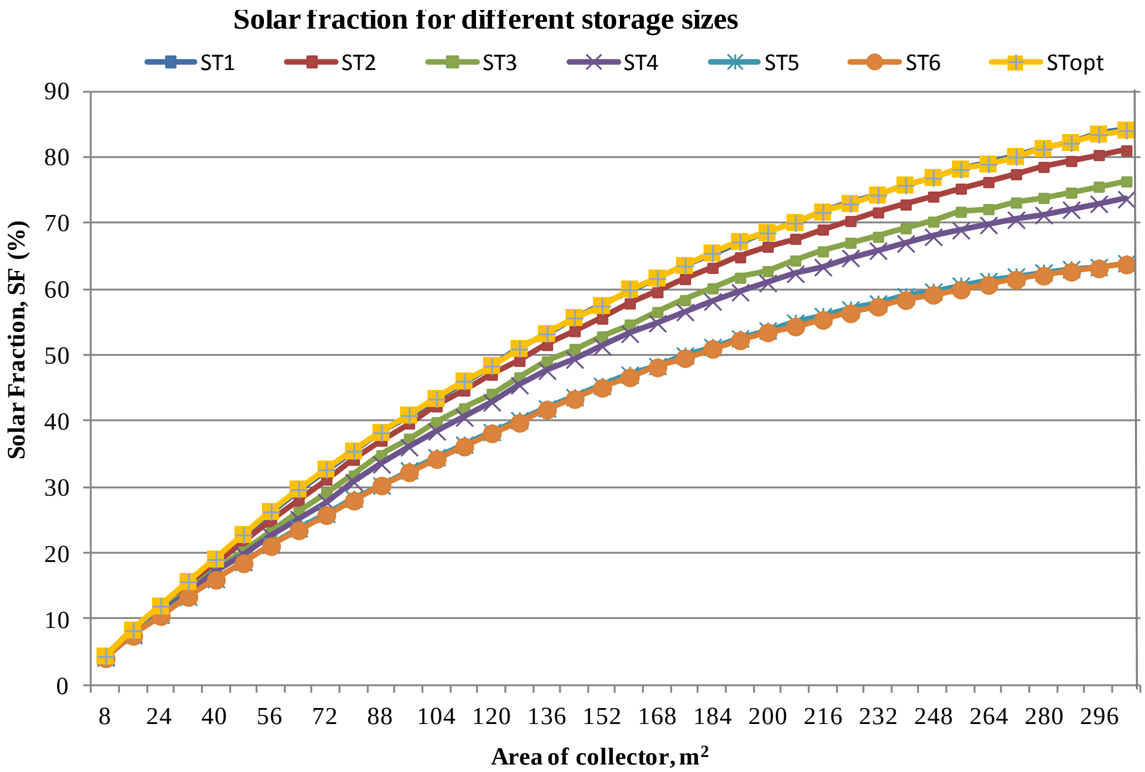

Fig. 6 Comparison of SF for optimum storage size with different storage sizes

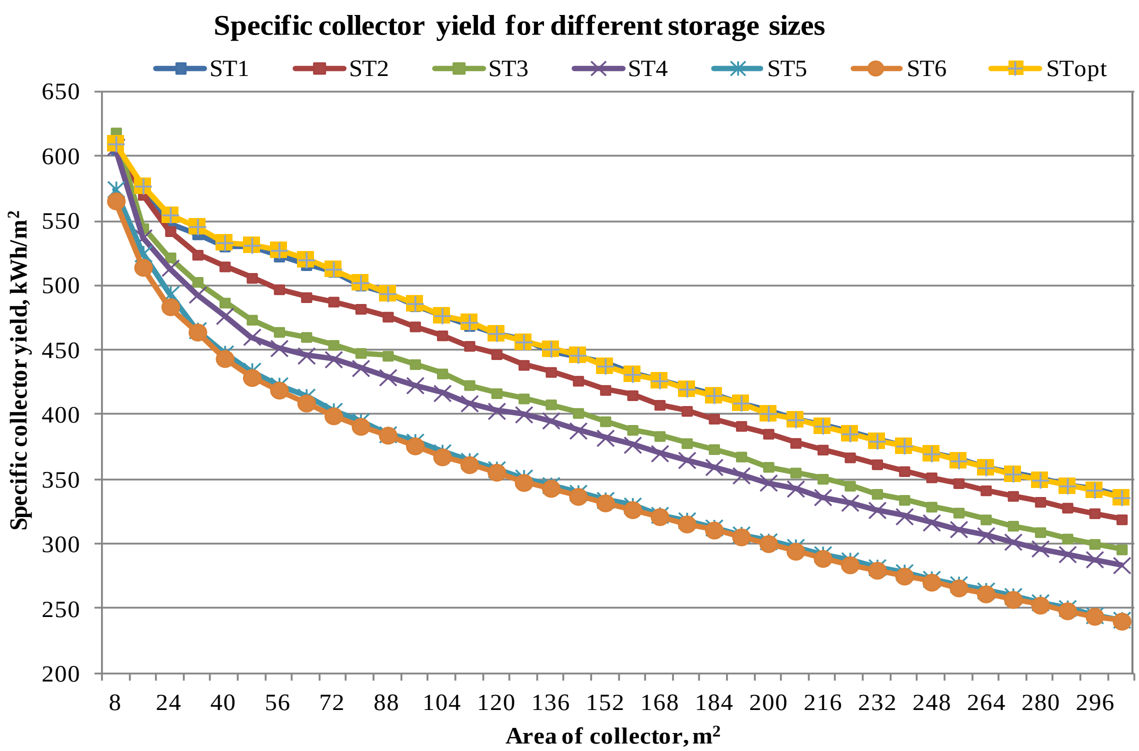

Fig. 7 Comparison of specific collector yield for optimum storage size compared to different storage sizes

The NPV using optimum storage equation for different ieff values and specific collector cost of 200€ m-2 is shown in Figure 8. The optimum area of collector also varies with different i_{eff} values. The figure shows that NPV does not reach positive for all ieff values that is due to the higher initial costs of solar collectors and absorption chiller (400€ kWc^{-1}) and lower natural gas prices in conventional system. The optimum area of collector is 160 m^2 for i^{eff} value of 4.5 and 3.5%, 184m^2 for 2.5% and 216m^2 for 1.5 and 0.5%. The optimum area of collector increases by decreasing i_{eff} value resulting higher solar fraction. The average annual solar fraction for collector areas of 160m^2, 182m^2 and 216m^2 is 60%, 65.5% and 72% respectively. The payback time (PBT) of SAHC system is above 20 years due to higher initial system units costs. Therefore, subsidies/incentives are required to make the system cost beneficial and to lower the PBT within acceptable limits.

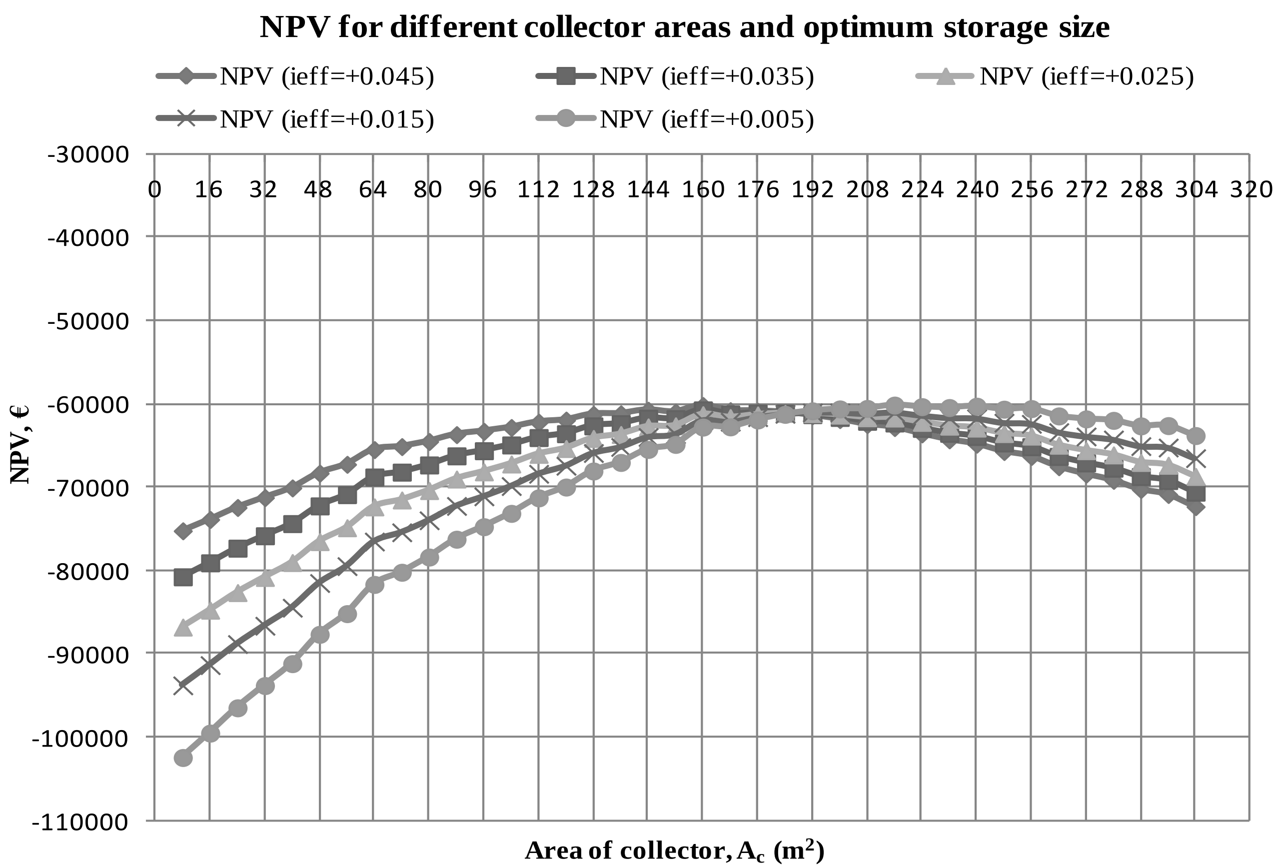

Fig. 8 NPV for different ieff values

For optimum storage size and area of collector (216m^2) for i_{eff} value of 0.5%, the contribution of solar energy (without considering pipes and storage tank losses) and auxiliary energy consumption for SHW, space heating and space cooling against energy demand of the building is shown in Figure 9. The annual solar fraction for SHW, space heating and cooling is 98%, 93% and 69% respectively while the overall annual solar fraction is 72%. The figure indicates that negligible amount of auxiliary energy is required during heating season due to small heating demand of the building. The auxiliary energy required during cooling season is necessarily during morning hours to heat the storage tank and remaining during days with scarce or no solar radiation. The monthly solar fraction (SF) for space heating and space cooling is shown in Figure 10. The SF space heating varies between 87 and 100% during heating season and solar fraction cooling between 55 and 100% during cooling season.

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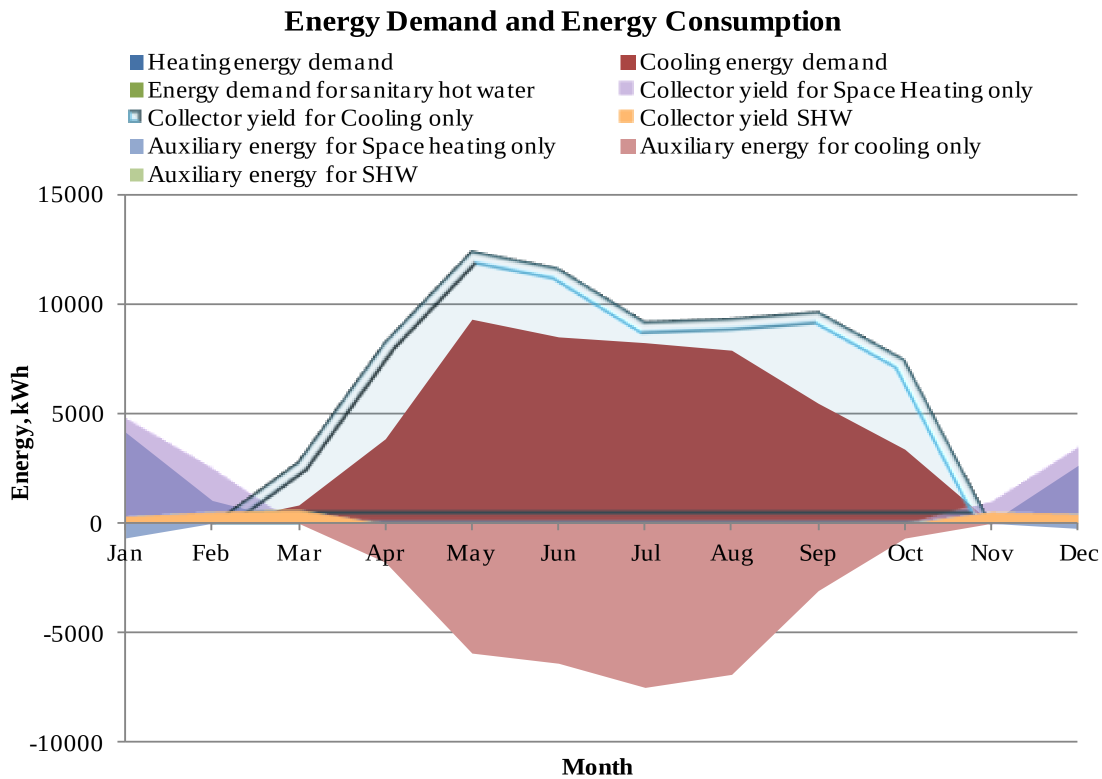

Fig. 9 Energy demand vs. energy consumption

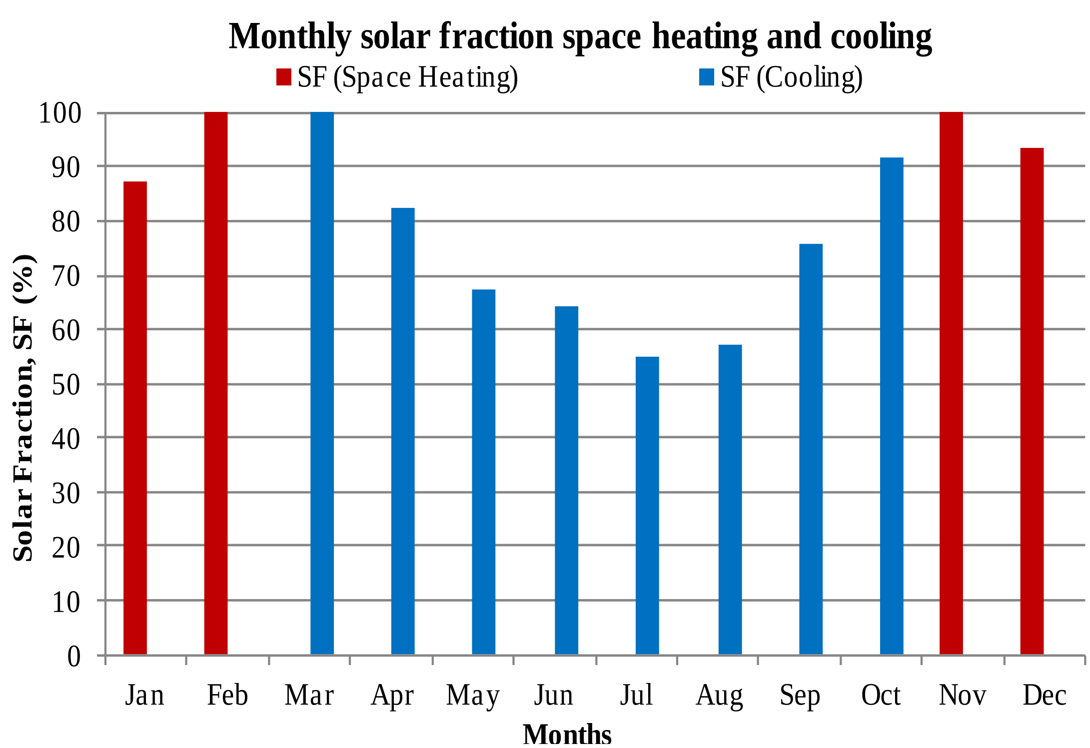

Fig. 10 Monthly SF for space heating and space cooling

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5. Conclusions

Solar energy systems performance is much more dependent to variation in collector area and storage size. However, for a given building size and typology, the most important factors to optimize collector area and storage volume also include climatic conditions which determine the heating and cooling needs, the financial parameters (interest rates, energy cost increase rate) and economic (installation costs, energy cost) boundary conditions. A sensitivity analysis of SAHC system has been carried out under climatic conditions of Faisalabad and its economic feasibility has been calculated using maximization of NPV. Both storage size and collector area has been optimized using different economic boundary conditions. Results show that optimum area of collector lies between 0.26m^2 to o.36m^2 of collector area per m^2 of conditioned area for i_{eff} values of 4.5% to 0.5%. The optimum area of collector increases by decreasing effective interest rate resulting higher solar fraction. The NPV was found to be negative for all i_{eff} values which show that some incentives or subsidies are needed to make the system cost beneficial and payback to reduce 20 years. The reason for higher payback period is lower current prices of natural gas in the country. However, the natural gas prices have started increasing rapidly which will reduce payback below 20 years in few years making solar cooling systems as an attractive option. Results also show that solar fraction space heating varies between 87 and 100% during heating season and solar fraction cooling between 55 and 100% during cooling season indicating potential of huge primary energy savings.

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